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The Aluminum Stabilized Conductor For The Fermilab DØ Solenoid *

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The aluminum stabilized conductor for the superconducting 2T solenoid for the DØ detector at Fermilab has been designed, fabricated, and tested. A Rutherford cable of Cu:NbTi multifilamentary superconducting strands was clad with 4N8 aluminum using the "conform" continuous extrusion technique. The quality control measurements made during the production of the conductor are discussed and measurements of the degradation in I_c caused by the cabling and cladding are presented. The characteristics of the soft solder joints used in the coil are described.

INTRODUCTION

The DØ solenoid [1], designed and fabricated by Toshiba Corporation, is wound with aluminum stabilized superconductor which is indirectly cooled. The limited cooling of the coil places stringent demands on the performance of the conductor. Field purity requirements also place constraints on the mechanical tolerances of the finished conductor. Ultrasonic soldering was selected to make joints between conductor lengths.

CONDUCTOR DESIGN

The DØ solenoid provides a working field of 2.0 T with good overall homogeneity which is achieved with two winding layers each having a region of enhanced current density at the ends of the magnet. The peak field in the conductor is 2.34 T and an operating current of 4800 amperes was chosen to ensure good quench safety and to match an existing power supply. A generous critical current margin in the superconductor and high RRR in the aluminum consistent with the magnetic stresses on the conductor serve to maximize the stability of the magnet. The conductor was specified to operate at

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no more than 55% I_c during chargeup when the conductor temperature is estimated to reach 5.0 K, and the RRR at 0T was specified to be not less than 800. The higher current density conductor for the magnet ends is made using the same superconductor but a lesser amount of aluminum stabilizer. The important parameters of the conductor are summarized in Table 1:

Table 1: Conductor Parameters

Parameter	Specified	Measured
Finished Conductor		
Grade 1	5.34 x 14.8 mm	Tolerances Met: ± 0.05 mm
Grade 2	4.02 x 14.8 mm	Tolerances Met: ± 0.05 mm
Aluminum RRR	$\geq$ 800 at 0 T	1300 – 2100
Cable Pullout	$\geq$ 10 MPa	14.9 – 32.9 MPa
Unbonded cable		$\leq$ 10 cm both sides
Aluminum Tensile Strength	$\geq$ 15 MPa	$\geq$ 19 MPa
I_c (2 T, 4.2 K)	$\geq$ 18400 A	$\geq$ 22000 A (extrapolated)
Cable		
Strands	18	18, no joints
Transposition	80 ± 10 mm	82 – 83 mm
Compacted Size	7.8 x 1.45	σ_t=0.0073 mm, σ_w=0.0068 mm
I_c (2 T, 4.2 K)		1367 x 18 = 24606 A
		$\geq$ 22700 A (extrapolated)
Strand		
Diameter	0.85 mm	0.848 mm average
Cu:NbTi	1.34 ± 5%	1.27 – 1.43
Number Filaments	$\geq$ 54	54
Filament Diameter	$\leq$ 80 microns	74.0 – 76.7 microns
Twist pitch	20 ± 10 mm	20 – 22 mm
Copper RRR		144 – 169
I_c (2 T, 4.2 K)	$\geq$ 1225 A	1384 A ave, 1316 min

CONDUCTOR TESTS AND INSPECTIONS

Strand

Four Cu/NbTi billets were prepared and drawn for the cable strands. Continuous eddy current testing and strand diameter measurements (using a laser micrometer) monitored strand production. The copper RRR, Cu:SC ratio, twist pitch, and I_c (4.2 K, 0.1 μvolt/cm) were measured for samples cut from each end of each of the strands. Cross sections were examined for filament spacing and diameter uniformity, and filament damage after bending each sample at 6 mm radius was monitored. The mean J_c at 5 T, 4.2 K in the NbTi was 3186 A/mm^2. N-factors (from the log/log fits to the resistive transitions) ranged from 49 to 57 at 2 T. The measured data from the eight strand samples are presented in Table 1.

Cable
The eight finished strands (typical length 20 – 33 km long) were cut as required to make up 18 pieces each for two Rutherford cables. Samples of the cables were disassembled and I_c measurements made on constituent strands. The cabling operation did not degrade I_c at 2 T more than 3.8% for any sample. The strand sample data are shown in Table 1. One full-cable sample was measured in fields above 4 T and the 2 T critical current shown in Table 1 was obtained by linear extrapolation from the measured points. The 5 T n-value for the sample tested was 48. The field values were corrected for conductor self-field effects. An extrapolation procedure which more realistically reflects the expected non-linear behaviour of well-optimized NbTi predicts an I_c at 2 T of 25900 Amperes.

Stabilized Conductor
The "conform" process rather than familiar hydrostatic extrusion was selected for the application of the pure aluminum to the cable. 99.998% pure aluminum was prepared as a feed wire 9 mm dia for use in the conform process. Chemical analysis of the aluminum billets showed Si $\leq$ 1.4 ppm, Fe $\leq$ 3.7 ppm with RRR $\geq$ 1400.
During the conform process the pure aluminum wire was continuously fed to the conform machine where it flowed onto the preheated superconducting cable inside a heated extrusion chamber which was inerted with nitrogen. A special die located the cable and established the final profile of the aluminum. The cable speed during the process was approximately 7 m per minute. The central 1 mm of each wide face of the cable/aluminum interface of the finished conductor was inspected ultrasonically and eddy current inspection was also made of each wide face of the outer aluminum surface. Two lengths each for the two final conductor cross-sections were clad with aluminum.
Samples were cut from the finished conductors and the resistance of the cable to pull-out from the aluminum stabilizer was measured, cross section dimensions were measured, the RRR and tensile yield strength of the aluminum was measured, the bond zone between the copper and the aluminum was inspected both before and after extreme bend tests, and I_c measurements were made by removing strands from the conductor. The RRR and pull-out measurements guided the cropping of the conductors for winding in the coil.

Full-Conductor Tests
I_c measurements were also made on two of the sample lengths at fields above 5 T and the 2 T value for the lesser sample shown in Table 1 obtained by linear extrapolation. The 7 T n-value for the sample was 46. The more realistic extrapolation procedure mentioned above for the cable predicts a 2 T I_c of 25100 Amperes for this fninshed conductor sample.
One of the samples selected for the full-conductor test had been cropped for rejection and was known to contain regions of cable poorly bonded to the aluminum stabilizer. During the testing of this sample no unstable resistive transitions were observed at the critical current values, and at moderate currents and high fields stable resistive zones could be established by the use of a heater because the sample was immersed in liquid helium. The resistive zones could be made to propagate or collapse smoothly by manipulating the transport current in the sample. Quench velocity measurements showed the inductive effects of current transfer into the high purity aluminum.
The degradation in I_c of the strands from the cabling and cladding operations as obtained from the disassembled cable strand measurements from the final conductor lengths were all quite similar.

In Table 2 are seen the results for one of the final conductor lengths. Added to the table are the results of the high field measurements made on the full-cable and full-conductor samples. Note data from three different conductor lengths is tabulated. Evidently estimating the full-conductor I_c by disassembling and measuring the strands is conservative.

Table 2: J_c (4.2 K) Measurements

Strands/Cable	2 Tesla	3 Tesla	4 Tesla	5 Tesla	6 Tesla	7 Tesla
Average Virgin Strand	1406	1155	968	802	643	
Average Cabled Strands	1360	1118	941	783	629	
Cabling Degradation [%]	3.3	3.2	2.8	2.4	2.2	
Average Extruded Strands	1347	1101	917	753	598	
Conform Degradation [%]	1.0	1.5	2.6	3.8	4.9	
Times 18 Value	24246	19818	16506	13554	10764	
Full Cable				14843	11780	8717
Stabilized Conductor				14377	11410	8443

Inspection Documents

In Figure 1 is seen a typical finished conductor cross section, and in Figure 2 a typical measurement of the final RRR of the aluminum.

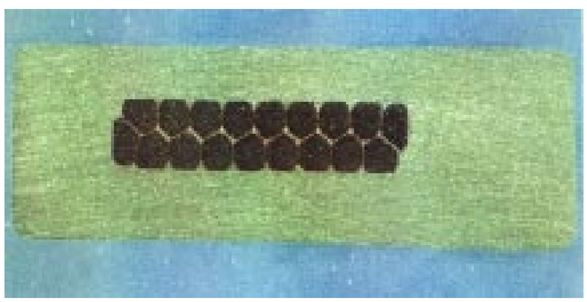

Figure 1: Finished Conductor

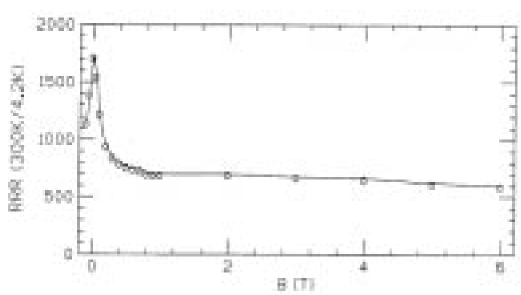

Figure 2: Final Aluminum RRR

In Figure 3 is seen a portion of the ultrasonic inspection for one conductor length. The periodic segments indicated as poorly bonded on one side are about 20 cm long and recur every 1.8 m which is also the circumference of a wheel in the conductor preheating fixture. Destructive inspections of such segments showed the presence of fissures between the cable and the aluminum. All other conductor lengths were essentially free of such defects. A Minimum Quench Zone calculation was made to estimate the longest length of conductor that might recover the superconducting state after a perturbative transition to the resistive state. For the conductor with the smaller amount of aluminum stabilizer this length is approximately 9 cm. The ultrasonic inspection indicates that no totally unbonded lengths of cable substantially greater than this exist in the conductor.

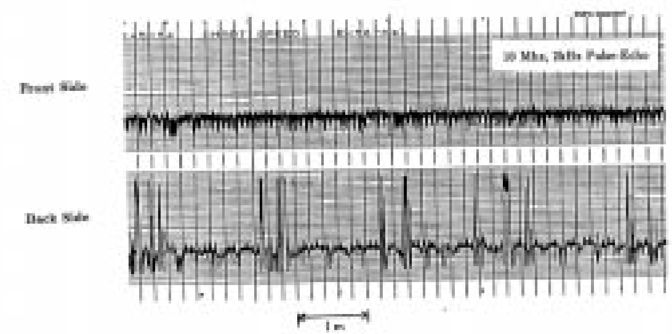

Figure 3: Ultrasonic Inspection

In Figure 4 is shown a surface emission microphotograph of the bond region between the aluminum and the copper. The copper is on the left, the aluminum on the right. The bond layer is typically about 1.0 micron thick.

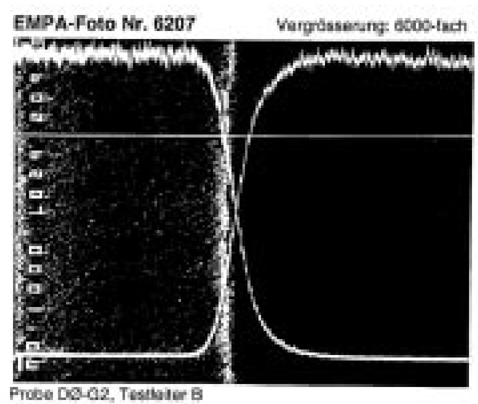

Figure 4: SEM Scan of Bond

ULTRASONIC SOLDERING

Ultrasonic soldering was selected to make conductor joints without the use of chemical flux. Joints at the current density transitions in the magnet are made by overlapping the conductors one full turn. The conductor facing surfaces are tinned using Sn/Pb 63/37 solder using a heating fixture and an ultrasonic soldering tool. Joints are made by reheating the pretinned conductors and adding a ribbon of Sn/Pb 40/60 solder to form the bond. The extra Pb is added to the joint to increase the low temperature ductility of the bond. The solder layer average thickness in the joints is about 60 microns. A lap shear test of a soldered joint at 77 K showed nominal shear strength of about 8 MPa. A similar test at room temperature showed nominal shear strength of about 10 MPa. A lap joint about one square cm in area made with 50/50 Sn/Pb solder had a resistance of 25 nano-Ohms at 4.2 K, 0 T.

CONCLUSIONS

The conform extrusion technique was used to apply pure aluminum stabilizer to a Rutherford cable of superconducting strands. This technology is novel for the cladding of superconducting cables. It provides the means to clad cable at speeds up to 10 – 12 meters per minute without major degradation of the superconducting cable, and it results in a stabilized conductor that has precise overall cross section, good tolerances on the interior location of the cable, and reasonably uniform quality of the bond between the cable and the pure aluminum. ULtrasonic soldering provides a means of making soft solder joints for the stabilized conductor without the need for electrochemical plating.

REFERENCES

1 B. Squires, *et al.* "Design of the 2 Tesla Superconducting Solenoid For the Fermilab DØ Detector Upgrade", Advances in Cryogenic Engineering (1993), 39, 301-308.